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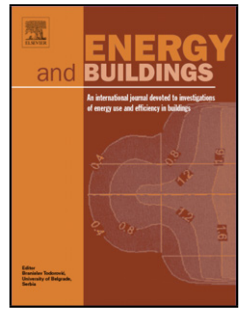

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PII: S0378-7788(13)00524-0
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2013.08.027
Reference: ENB 4468

To appear in: *ENB*

Received date: 9-7-2013
Accepted date: 17-8-2013

Please cite this article as: M. Thalfeldt, E. Pikas, J. Kurnitski, H. Voll, Facade design principles for nearly zero energy buildings in a cold climate, *Energy and Buildings* (2013), http://dx.doi.org/10.1016/j.enbuild.2013.08.027

Facade design principles for nearly zero energy buildings in a cold climate

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Abstract

Cost optimal and as energy efficient as possible façade solutions, including window properties, external wall insulation, window-to-wall ratio and external shading were determined with energy and daylight simulations in the cold climate of Estonia. Heating dominated in the energy balance and therefore windows with higher number of panes and low emissivity coatings improved energy performance. The window sizes resulting in best energy performance for double and triple glazing were as small as daylight requirements allow, 22-24% respectively. For quadruple and hypothetical quintuple glazing the optimal window-to-wall ratios were larger, about 40% and 60% respectively, because of daylight utilization and good solar factor naturally provided by so many panes. The cost optimal façade solution was highly transparent triple low emissivity glazing with window-to-wall ratios of about 25% and external wall insulation thickness of 200 mm (U=0.16). Dynamic external shading gave positive effect on energy performance only in case of large window sizes whereas due to high investment cost it was not financially feasible. Limited number of simulations with Central European climate showed that triple glazing with double low emissivity coating and window-to-wall ratio of about 40%, i.e. slightly larger and with external shading compared to Estonian cost optimal one, clearly outperformed conventional design.

Keywords: Façade design, windows, fenestration, daylight, nearly zero energy buildings, cost optimality, energy simulations

1. Introduction

In order to achieve nearly zero energy building (nZEB) requirements by 2021 in a cold climate energy efficient façades are one important factor in the design of such buildings. Facade performance including windows, opaque elements and shadings has strong impact on heating, cooling and electric lighting energy needs as well as on daylight.

So far, in office buildings, often large windows have been used without special measures, resulting in high heating and cooling needs, high investment cost and often poor solar protection and glare. Double and triple pane windows are currently most commonly used, however one can choose between highly transparent windows, which do not offer good solar protection and may cause high cooling costs, or ones with good solar protection qualities, but lower visible transmittance, which result in high heating cost due to larger windows required by daylight standards. Evidently low and nearly zero energy buildings will need more careful design to optimize the facade performance. It is important to assure daylight and views outside which both have proven evidence on occupant satisfaction and productivity.

Several complex analyzes have been made about façade design influence on buildings' energy consumption. Poirazis et al.[1] conducted office building energy simulations studying window-to-wall ratios (WWR) between 30% to 100%, different glazing, shading and orientation options. It was concluded that office buildings with lower WWR consume less energy. Similar analyzes were made by Motuziene and Joudis [2] about office building in Lithuania. The results showed that optimal WWR was 20-40%, however it was noted that there will be problems fulfilling daylighting requirements. Susorova et al. [3] simulated office buildings in 7 different climates and concluded that in cold climates increasing WWR increases office buildings' total energy consumption. Using energy simulations of an institutional building Tzempelikos et al. [4] came to conclusions that substantial energy savings can be achieved using an optimum combination of glazings, shading devices and controllable electric lighting systems. Johnson et al. [5] optimized daylighting use and studied the sensitivity of orientation, window area, glazing properties, window management strategy, lighting installed power and control strategy. The results showed that saving can be significant with automatically controlled lighting, however total energy consumption must be kept in mind as analyzed parameters influenced the energy use of HVAC greatly. Boyano et al. [6] studied the effect of building envelope thermal resistance and also lighting system efficiency on office building energy efficiency and concluded that lighting plays significant role in energy use. The importance of taking into account the interaction between lighting and HVAC system was also stressed by Franzetti et al [7].All of the authors mentioned previously, have done thorough investigation of office building façade, however windows with U-values below 1.0 W/(m^2 K) have been rarely studied. One of the few studies, that has investigated office building energy use with glazing of extremely low U-values was conducted by Grynning et al [8]. The results showed that lower U-values of windows result also in lower energy consumption and the optimum solar heat gain coefficient (SHGC) is 0.4. It was also concluded that cooling energy dominates the energy need, however cases with WWR of 55% were simulated and therefore it is still unclear whether these results also apply in case of different WWRs.

As previous studies have shown that lowering WWR increases energy efficiency, but on the other hand it also reduces daylighting efficiency. Therefore it is important to set lower limits to window sizes. Estonian Standard EVS 894:2008 “Daylight in dwellings and offices” [9] states that average daylight factor should not be below 2% in office rooms. Voll and Seinre [10] have used same guidelines in their description of a method for optimizing fenestration design for daylighting to reduce heating and cooling loads in offices. In addition to that maximum WWR values were derivated so that heating and cooling loads of office rooms would not exceed limit values.

A very common way of assessing feasibility of investments is calculating payback period of different cases, however it may not reveal the best option. Directive 2010/31/EU, EPBD [11] stipulates that EU members must ensure that energy performance requirements of buildings are set on cost optimal level. This means that primary energy requirements are set at level, where life cycle cost is minimal. The development of national requirements has been described by Kurnitski et al. [12], who presented calculation results for residential buildings using lowest NPV of building costs as the criteria for cost optimality. Life cycle cost analysis was proposed as a part of “Integrated Energy-Efficient Building Design Process” by Kanagaraj and Mahalingam [13]. It was found that considerable energy savings could be achieved using the process. Life-cycle cost analysis was also used by Kneifel [14] in his simulation-based case study of several building types including also office buildings.

The purpose of the study is to give guidelines of office buildings façade design from the perspective of energy-efficiency and daylighting to architects, engineers, real-estate developers etc. In this study we derived optimal design principles for a cold climate regarding window sizes, solar protection, thermal insulation and daylight leading to optimized total energy performance of office buildings. Special attention was paid to highly insulated glazing elements with U-values of 0.6 W/(m^2 K) and below to 0.21 and high visible light transmittance of about 0.5-0.7. Energy and daylight simulations were conducted for model office space representing typical open plan offices. Window to wall ratio, solar heat gain coefficient, visible transmittance, solar shading and external wall U-value was varied in order to analyze energy performance. Lower limit of window size was determined by the average daylight factor criterion of 2%, but cases with larger windows were also analyzed. Investment cost of windows and external walls was compared to generate simulation cases so that optimal insulation thicknesses would be used with each glazing variant. Payback times and net present values (NPV) of studied cases were calculated to assess cost effectiveness.

The investment cost and NPV calculations have been thoroughly described in a companion paper by Pikas et al [15]. The economic results necessary to determine optimal façade design solutions have been taken from the companion paper.

2. Methods

Key factors of a façade mostly influencing the energy performance of a building, such as window type, wall insulation, window-to-wall ratio (WWR) and shading devices, were optimized in the case of a generic office floor model for the lowest life cycle cost and alternatively for the best achievable energy performance. Step by step approach was used to start with double and triple pane glazing units and WWR determined by the daylight factor criterion. In total, four steps were used to determine the most energy efficient and cost optimal solutions for each orientation. These included:

1. Selection between highly transparent vs. solar protection windows;
2. Determination of the optimal size of windows (WWR) with fixed initial U-values of opaque elements of external walls;
3. Determination of optimal external wall insulation thickness;
4. Assessment of cost optimal and most energy efficient solutions for each façade.

2.1 Generic office floor model

Energy simulations were conducted on the basis of a generic open-plan office single floor model that was divided into 5 zones - 4 orientated to south, west, east and north respectively and in addition one in the middle of the building (Figure 1). The longer zones consisted of 12 room modules of 2.4 m and shorter ones of 5 room modules, resulting in inner dimensions of the floor 33.6 x 16.8 m. In all cases the heating was district heating with radiators (ideal heaters in the model), and air conditioning with room conditioning units (ideal coolers in the model) and mechanical supply and exhaust ventilation with heat recovery was used. The working hours were from 7:00 to 18:00 on weekdays and the usage factor of heat gains during working hours was 55%. Ventilation worked from 6:00 to 19:00 on weekdays. The lighting was with dimmable lamps and daylight control with setpoint of 500 lx in workplaces. The position of workplaces used for the control is shown in Figure 1. Either external or internal blinds were automatically drawn, when total irradiance on the façade exceeded 200 W/m^2 to avoid glare. The initial data of simulation model is shown in Table 1. Lighting and shading control principles were adopted from [16]. The energy simulations were conducted with well-validated simulation tool IDA ICE 4.5 [17] and the test reference year of Estonia was used [18]. Some simulation were made for comparative purposes with Central European climate data, ASHRAE TRY for Paris was used [19]. The primary energy factor for district heating is 0.9 and for electricity 2.0.

Figure 1 The generic model of single floor of an office building constructed with 2.4 m room module – plan and 3D view. The locations of workplaces used for control of lighting are marked in the plan.

Table 1 Input data of office rooms and HVAC systems for energy calculations.

2.2 Minimum window size and the properties of the windows

The criterion of 2% average daylight factor [9] in the daylight zone (up to 4 m from the external wall) was used to calculate minimum window sizes. The open-plan offices were divided into 2.4 meter wide modules and office rooms consisting of two modules were used in daylight and cooling load calculations. The bottom edge of all windows was 0.9 m from the floor and the height was 2.2 m. The description of perspective office room is shown in Figure 2.

Figure 2 Floor plan of the open plan office module (2.4 m) and the section showing window and room height.

The average daylight factor of office rooms is calculated according to the following equation [9]:

$$D = \frac{T \times A_w \times \theta \times m}{A \times (1 - R^2)} \quad (1)$$

Where,

D - average daylight factor, -

T – scattered light transmittance of glazing (90% of visible transmittance τ), -

Θ – sky angle, 80°

m – clearness of the glazing, 0.9

A – total area of all interior surfaces (incl windows), 109.4 m^2

A_w – total glazed area of windows, m^2

R – mean surface reflectance, 0.5

The glazing area can be calculated with the following formula:

$$A_w = \frac{D\times A\times(1-R^2)}{T\times\theta\times m} \qquad (2)$$

The description of all glazing variants studied is shown in Table 2. The window widths are chosen as small as possible with a step of 50 mm so that average daylight factor would not be below 2%. Variant names are made up so that the first number stands for the number of panes, “C” for clear, highly transparent and “D” for tinted solar protection windows. “e“ or “-” describe whether there is external shading or not respectively. For example “2/C/-“ stands for a double glazed, clear window without external shading. Initially, 200 mm external wall insulation thickness (U=0.16) was used with 2 and 3 pane windows and 300 mm insulation thickness (U=0.11) with 4 and 5 panes. The double, triple and quadruple glazing properties were calculated using window manufacturers’ calculation tools. Generally low emissivity coating (ε=0.03) was used in all gaps between panes (except for glazing with air fillings, only used in Ch 3.4). In case of solar protection window cases the outer pane was a solar protection glass with low emissivity also. The quintuple glazing representing not a standard product was calculated with detailed window model of IDA ICE which is based on the method of [20]. It is remarkable that the highly transparent quadruple and quintuple glazing cases have solar heat gain coefficient (g-value) as low as 0.36 and 0.24 respectively, so basically they can also be considered as solar protection glazing. The U-value of frames for double glazed windows was 1.2 W/(m^2 K) and for 3 and higher number of panes it was equal to the U-value of glazing.

Table 2 Description of clear and solar protection glazing variants and initial U-value of opaque elements of external walls.

2.3 Selection procedure for simulation cases

In first step, it was determined whether highly transparent or tinted solar protection windows allow reaching better energy efficiency. For that purpose, double and triple glazed window cases with minimum window sizes were simulated (results reported in Ch. 3.2). Larger window sizes were not studied, because these common windows have U-values several times higher than external walls and therefore using highly transparent windows with lowest possible size is in heating dominating climate more energy efficient [21] than using large windows with good solar protection.

In the second step, simulation cases with several WWRs were created to find the optimal size of windows, because with the U-values closer to external wall U-values, the smallest possible window might not be the optimal. As large windows may cause high cooling need, then the influence of external shading was also tested. Simulated cases (results in Ch. 3.3) covered:

- The range of WWR of 23.9 to 60% for each façade;
- Glazing from 3 to 5 pane with U-values between 0.54–0.21;
- With and without external shading on East, South and West facades.

In the economic analyses, in order to find balance between insulation thicknesses and glazing types, the investment cost of façade element combinations was compared to energy cost and primary energy of each combination as the third step of the analysis. The description of studied combinations is shown in tables 4, 5 and 6, figure 3 and results are reported in Ch. 3.4. Estonian cost data of windows showed that double windows and triple glazing with air filling cost approximately as much as triple glazing with argon filling. For that reason, optimal WWR analyses were conducted with triple glazing with argon filling or quadruple and quintuple glazing with krypton filling and all insulation thicknesses were studied only for these two glazing types.

Table 3 Cost data of opaque elements of external wall, which were concrete Sandwich elements with mineral wool insulation

Figure 3 Section of external wall, the thickness on insulation varies by cases

Table 4 Cost data of windows, including both glazing units and aluminum profiles with thermal breaks. The window sizes vary for different glazings which affects the development of window cost due to different proportions of frames. Window cost has been more thoroughly described in the companion paper [14].

Table 5 Investment cost of external wall as a function of insulation thickness and glazing type. All costs in the Table are investment costs per m^2 of conditioned floor area, €/m^2.

The final fourth step was to find out the most energy efficient and cost optimal fenestration design cases for each orientation. The criterion for best energy efficiency was lowest primary energy use and for cost optimality the lowest NPV of investment and energy cost for 20-year period which followed the calculation method of Cost Optimal regulation [11] with discounting interest rate of 1.5%. Simulation cases with double, triple, quadruple and quintuple glazing variants with the best properties and minimum WWRs were created. Furthermore each glazing variant was simulated with and without external shading. The description of simulation cases is given in table 7 and results are reported in Ch. 3.5.

Table 6 Final simulation cases

3. Results

3.1 Daylight calculations

Daylight calculations (Eqs. 1 and 2) showed that minimum window-to-wall ratio (WWR) of highly transparent windows was between 21% and 29.5%. Minimum WWR increased together with the number of panes as visible transmittance decreases. The minimum WWRs of solar protection windows exceeded 30%. The WWR dependency of visible transmittance of window glazing has been shown in Figure 44 and the minimum window sizes in 5.

Figure 4 Minimum window to wall ratio depending on visible transmittance of window glazing

Figure 5 Window sizes of glazing variants (Variant codes correspond to Table 2, e.g. 2/C 0.95 m 21.6% means double, highly transparent window with width of 0.95 m and the window-to-wall ratio 21.6%). 2.4 m is the maximum width of the window providing WWR 60%.

3.2 Highly transparent vs. solar protection windows

In all cases room heating dominated the energy use and it was greatly affected by the size of windows as shown in Figures 6 and 7. Supply air heating and cooling had next largest energy needs followed by lighting. Tinted windows with larger size remarkably increased space heating need. Lighting electricity varied by orientations, but was practically the same for each glazing variant as the windows have been sized according to daylight criterion. The space cooling energy need fluctuated several times, however the influence on total energy use was low.

Compared to highly transparent glazing, clear solar protaction windows showed slightly worse energy use on each façade.

Figure 6 Energy need in zones with highly transparent and solar protection windows with minimum size according to the daylight criterion of 2%.

Figure 7 Delivered energy for the cases of Figure 5.

The comparison of highly transparent and tinted solar protection windows showed that in case of similar U-values highly transparent solar protection glazing results in better energy efficiency as can be seen from primary energy shown in Figure 8.

Figure 8 Primary energy for the cases of Figure 5 and 6.

3.3 Optimal window-to-wall ratio

The simulation cases with fixed insulation thickness resulted in delivered and primary energy shown in Figures 9 and 10. Generally increasing WWR increased cooling energy use and decreased lighting electricity. Space heating energy use increased with triple windows, fluctuated with quadruple windows and decreased slightly with quintuple windows if WWR was increased as shown in Figure 9. The use of external shading in all cases increased heating and lighting energy use and decreased cooling energy, whereas it improved primary energy use only in case of larger window sizes. In addition the positive effect of external shading was higher for east and west orientations. For the north façade external shading was not studied. In Figures 9 and 10 the effect of external shading is shown only for cases where primary energy decreased compared to the case without external shading. For triple windows the increase of WWR increased delivered energy, which made WWR 24.1% the most energy efficient case. However in the north façade WWR 37.5% gave lower primary energy than 24.1% due to lower lighting electricity despite slight increase in heating and cooling energy.

Figure 9 Delivered energy results of the cases used to determine optimal WWR with initial fixed insulation thickness (200 and 300 mm for 3 and 4 pane respectively). Delivered energy is given in each zone as a function of window type, external shading, orientation and window size. Case codes are described in Table 2, e.g. 3/C/-/23.9% means 3-pane, clear solar protection glass, no external shading and WWR=23.9%.

In case of quadruple windows the following results can be seen from Figure 10:

- In all cases, heating and lighting primary energy decreased when WWR was increased from 26.1% to 37.5%. At 60% WWR, the cooling energy started to dominate on south, east and west facades.
- Most energy efficient south orientated case was with WWR 37.5% and without external shading
- East and west facades most energy efficient case was with WWR 60% and external shading, whereas without external shading WWR 37.5% provided slightly higher primary energy.
- On the north façade WWR 60% resulted in lowest primary energy because of significant decrease in lighting energy without any important increase in cooling energy.

In case of quintuple windows the following results can be seen from Figure 10:

- In all cases, heating and lighting primary energy decreased when WWR was increased. At 60% WWR, the cooling energy increased significantly on south, east and west facades.
- Most energy efficient south and north orientated cases were with WWR 60% and without external shading.
- East and west facades most energy efficient case was with WWR 60% and external shading.

Figure 10 Primary energy for the cases of Figure 9.

3.4 Optimal external wall insulation thickness

The calculations since now have been done with insulation thickness of 200 mm for 3 pane and 300 mm for 4 and 5 pane windows. To determine the most sensible external wall insulation thickness Façade investment cost and net present values for a 20 year period were calculated for glazing variants described in Table 5. Financial analysis is fully reported in a companion article of this paper by Pikas et al [15]. In the following only the results necessary for creating final simulation cases are reported. The primary energy, investment cost and NPV of all cases are shown in figures 11 and 12. The insulation thickness which resulted in lowest NPV was 200 mm for most cases, which was chosen for final analysis for triple glazing variants. However compared to case with quintuple glazing and 200 mm insulation thickness both the investment cost and primary energy was lower for façade with triple windows and 300 mm insulation thickness. This made using 4 pane windows with 200 mm wall insulation insensible and 250 mm was chosen for final analysis of 4 pane glazing. A similar situation appeared between 4 panes/390 mm insulation and 5 panes/300 mm insulation cases so 390 mm of insulation thickness was chosen for quintuple glazing.

Therefore the following glazing and insulation thickness combinations were selected for final analyses (marked with red circles in figure 12):

- Triple glazing with argon filling and 200 mm – the cost optimal
- Quadruple glazing with krypton filling and 250 mm – the most relevant for 4 pane (in between the cost optimal and the most energy efficient)
- Quintuple glazing with krypton filling and 390 mm – the most energy efficient

Figure 11 Investment cost and primary energy of different glazing (all without external shading) and external wall insulation cases. Insulation thicknesses from left to right 150, 200, 250, 300 and 390 mm if not otherwise specified.

Figure 12 Net present value and primary energy for the cases of Figure 11.

3.5 Most energy efficient and cost optimal cases.

For the window types and insulation thicknesses selected in Ch. 3.4 energy simulations and economic analyses were repeated for optimal range of WWR with and without external shading. These results allow to determine optimal solutions refining the results of calculations done in Ch. 3.2 and 3.3 with initial, not optimal combinations. Compared to results shown in Ch 3.3 the external wall insulation thicknesses of quadruple and quintuple window cases have been changed to 250 and 350 mm respectively (based on Ch 3.4 results). Also the energy needs of different systems have been given (see figure 13) and in addition the effect of external shading has been shown for all cases except north orientation.

External blinds increased space heating energy need in all cases, whereas the effect was biggest on the south façade. The largest space cooling needs appeared in case of triple glazing with WWR 37.5% and when windows were sized according to daylight requirements the space cooling needs were rather insignificant. The increase of WWR caused remarkable reduction in lighting energy use, whereas external shading slightly reduced it.

Figure 13 Energy needs of final simulation cases for all zones. Insulation thicknesses determined in Ch. 3.4 are used.

Heating dominates the delivered energy of all cases, Figure 14. The effect of external shading in case of smaller window sizes on energy use becomes more obvious. Only the cases that have high space cooling needs receive positive effect on energy efficiency from added external blinds.

Figure 14 Delivered energy of final simulation cases.

The most energy efficient cases (lowest primary energy, Figure 15) were by orientation the following (also marked with red circles in figure 15):

- South – 5 panes with no external shading, WWR=60%, external wall insulation 390 mm
- East – 5 panes with external shading, WWR=60%, external wall insulation 390 mm
- West – 5 panes with external shading, WWR=60%, external wall insulation 390 mm
- North – 5 panes with no external shading, WWR=60%, external wall insulation 390 mm

In Ch 3.3 it was determined whether WWR 37.5% or 60% result in better energy efficiency for each glazing type on each façade and in figure 15 only the results of the more energy efficient WWR cases has been shown. For example in case of quadruple glazing the results for WWR 37.5% have been shown for south, east and west and in case of WWR 60% for only north.

Figure 15 Primary energy of final simulation cases.

The primary energy relationship to investment cost and NPV are shown in figures 16 and 17 respectively. The cases shown in the figures have been connected with lines if not otherwise specified in the following order: 3/C/37.5%, 3/C/23.9%, 4/C/26.1%, 4/C/37.5% and 5/C/29.5. Case 5/C/-/37.5% has been added for west facades as it resulted in better primary energy and NPV than similar case with lower WWR.

Figure 16 Investment and primary energy of final simulation cases. Three upper curves are with external shading (marked with *e*) and lower curves with more cases without.

Financially most feasible cases that had lowest NPV were by orientation the following (also marked with red circles in figure 17):

- South – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm
- East – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm
- West – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm
- North – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm

In south, east and west facades with triple glazing and no external shading WWR 37.5% resulted in worse energy performance than 23.9%, however the cost per area for windows was smaller than of external walls and therefore WWR 37.5% was most financially feasible. If triple windows would be more expensive than external wall with insulation thickness 200 mm, then the cost optimal WWR would be 23.9% in south, east and west facades.

Figure 17 Net present value and primary energy of final simulation cases without external shading.

3.6 Cooling load with and without external shading

External shading generally did not improve energy performance and if it did, then the investment could be so high that energy saving alone is not enough for the payback (economic analyses of external shading are provided in the companion paper [15]). However external shading has impact on HVAC systems, in the form of reduced capacity of chiller and cooling system. The effect of external shading on sensible cooling capacity of a 4.8x4.8 m room with 2 persons in it is shown in Figure 18. External shading has helped reaching very low sensible cooling capacities around 20 W/m^2 and below. Quadruple and quintuple glazing with minimum window sizes allows reaching reasonable cooling capacities around 40 W/m^2 without external shading, whereas WWR may be increased to 37.5% in case of 5 panes with shading. Small sized double and triple glazing and quadruple windows with WWR of 37.5% resulted in cooling capacities around 50 W/m^2 and higher. These cases also showed significant rise in room cooling needs compared to other simulation variants (see figure 13).

Figure 18 Office room cooling capacities of final simulation cases

3.7 Extending single floor model to full building model

The maximum allowed annual primary energy use of office buildings in Estonia is 160 kWh/m^2 and the requirements for low and nearly zero energy buildings are 130 and 100 kWh/m^2 respectively [22]. The primary energy consumption of most simulated cases shown in figure 10 and 14 remain below the nZEB requirement of 100 kWh/m^2, whereas in figure 14 information is shown in zones by orientations and the whole office floor has generally even lower energy consumption than the zones separately.

The generic floor model used in the analysis was very compact because of adiabatic floor and ceiling. The model is relevant for studying façade solutions, but the results may give a misleading impression about the simplicity of meeting nZEB requirements. In order to characterize the fluctuations in delivered energy related to compactness of buildings, external ceiling was added to the generic floor model. Two models were created: one had the most financially feasible solutions for each façade and the other the most energy efficient solutions. The roof U-values used for financially optimal and energy efficient cases were 0.10 W/(m^2·K) and 0.09 W/(m^2·K) respectively. Adding roof had expectedly the biggest effect on heating energy increase, decrease of cooling energy was smaller and lighting practically did not change at all. The increase of the delivered and primary energy was about 35% and 20% for both cases, whereas the influence on the energy efficient case was slightly higher as its initial energy use was lower. The fluctuation in the energy use of the simulation models is shown in figures 19 and 20. The heating energy increase of the whole building is higher than of any other zone located on the facades, which is caused by heat loss through the ceiling of the zone located in the center of the floor. The influence on cooling energy varies much from orientation to orientation, however the change is higher when initial space cooling energy forms a larger part of total cooling energy. According to the results of these two cases, a safety margin of 20% can be applied for the primary energy calculated with a typical floor model.

With these model simulating a full building, the primary energy use was 103.4 kWh/m^2 and 110.9 kWh/m^2 for energy efficient and economically feasible cases respectively which means that they fulfill low energy building requirements instead of nZEB ones. In order to reach nZEB level, on site energy production e.g. PV-panels must be used.

Figure 19 Energy use fluctuation of the most energy efficient cases

Figure 20 Energy use fluctuation of the financially most feasible cases

4. Discussion

Results show that the single floor model used for façade analyses was not relevant to describe a full building, because of very high compactness. Normally office buildings are not that compact as they have areas with large glazed areas (e.g. lobbies) and also the shape is less compact. An attempt was made to transfer the results from this model to a full building, by adding external roof to the model. In two calculated cases the delivered energy increased approximately 35% and primary energy 20%. These values depend on a specific building and were not analyzed further, because the aim of the study was to find optimal façade solutions. Previous experience shows that calculated 20% margin in primary energy could be slightly on the safe side for most of real office buildings, but still can be recommended for the scaling results from single floor model until the final results would be calculated with a full building model.

Usually windows are considered to be more expensive than insulated external wall, however in the current study it was the other way around for triple glazed windows and the NPV of this case was more affected by investment cost than energy use. If less expensive external wall assembly can be found, this will stress the principle of possibly small windows in the case of triple glazing. In any case, the results show the importance of economic calculation to be run in parallel with energy simulations, as cost optimal solution can really change the design.

According to the results, the largest energy use affected by the façade design in office buildings located in a cold climate was the heating energy. We ran some simulations with the climate of Paris to find out to what extent the results might apply for the temperate climate of Central Europe. Cost optimal and the most energy efficient cases (Ch. 3.5) were run without changes. For other cases similar U-values ofthe Elithis Tower [23] nZEB case study were used (1.1 W/(m^2·K) for windows and 0.3 W/(m^2·K) for external walls). For these cases 1.1 W/(m^2·K) was used for windows, and the less insulated external wall with U-value of 0.20 W/(m^2·K) was used. The results showed that the cooling energy starts to dominate and also proportion of lighting energy increased as is shown in figure 21. Due to larger cooling energy use the effect of external shading was positive in all the cases. Similarly to the climate of Tallinn, smaller sizes of double and triple windows resulted in better energy performance and there was a remarkable drop in heating energy use caused by triple glazing. However the heating energy still remained higher than that in cases with Estonian insulation. The situation could be different with higher internal gains, but this study used very small internal heat gains suitable for nZEB buildings.

Figure 21 Delivered energy in Paris. In two first cases the cost effective and most energy efficient façade solutions in Estonian climate are used. In other cases U-values were 1.1 for double glazing, 0.6 for triple glazing and 0.2 for external walls.

Triple glazing showed significantly better results in primary energy than double glazing as can be seen in figure 22. However, the performance of the case with Estonian most energy efficient façade was not achieved. This indicates that even in Central European climate, there is a need for improved façade components. Indeed the solutions feasible in a cold climate could not pay back because of lower heating need.

Figure 22 Primary energy in Paris for the cases of Figure 21.

Double-skin facades were not studied in this paper, however often used in modern office buidings as offering good protection to external climate and allowing to using lighter external blinds between skins. Double-skin facades also provide architects the opportunity to give the impression of a glass building without necessarily having to use large window areas that decrease energy performance. Another benefit is its ability to preheat the air between the building and closed double-skin façade which reduces ventilation heating costs, however the risk of over-heating makes the use of automatically controlled ventilation hatches necessary. On the other hand double-skin facade reduces the efficiency of using daylight and that also increases minimum window-to-wall ratios which finally results in increased space heating energy use as shown in this study. As the investment cost also rises, the feasibility of using double-skin facades becomes completely different question deserving another study to find optimal solutions.

Another aspect of façade solutions that requires more research is the control principles of external shading. External blinds were controlled according to a very simple algorithm in the analysis and that often resulted in reduced energy performance. More advanced control algorithms could be possible to develop in order to reach full effect of active shading.

5. Conclusions

Cost optimal and most energy efficient façade solutions, including window properties, external wall insulation, window-to-wall ratio (WWR) and external shading were determined with energy and daylight simulations in the cold climate of Estonia. These façade parameters were optimized for the lowest life cycle cost and alternatively for the best achievable energy performance to be used as design guidelines for architects and engineers working with facades in low and nearly zero energy buildings.

Heating dominated in the energy balance of office buildings in case of conventional windows and therefore improving the U-values of windows by increasing the number of panes and low emissivity coatings also improved energy performance. Optimal window sizes for double and triple glazing were as small as daylight requirements allow, because the U-values of these windows are relatively high compared to opaque elements of external walls and larger windows cause high heating and cooling energy use, which were not compensated by decreased electric lighting.

In the comparison of clear low emissivity glasses to tinted solar protection glasses and clear solar protection glasses with high visible transmittance the best energy performance was achieved with clear low emissivity glasses and the second best with clear solar protection glasses that followed the minimum size of windows determined by the daylight requirement. Also the cooling load was possible to keep at reasonable level with minimum size clear low emissivity glazing. Therefore all optimal cases found in this study were with clear glazing, where a low emissivity coating was in each gap between the panes.

In the case of high performance windows with quadruple and quintuple glazing and U-values of 0.3-0.2 windows heat losses become similar to opaque elements of external walls and the minimum window-to-wall ratios did not show any more the best energy performance. 4 and 5 pane clear low emissivity glazing provided also naturally good solar protection, because of high number of panes and coatings. Therefore the positive effect of larger windows on electric lighting and in some cases even on heating energy exceeded the negative effect on cooling energy increase. Best energy performance was achieved at 37.5% and 60% WWR in the case of quadruple and quintuple windows respectively.

Adding external shading reasonable window sizes increased primary energy as the initial space cooling needs were quite low and the increase in heating and lighting energy was not compensated, however a relatively simple control principle of shading was used in the current analysis. In the case of large double or triple glazing, external shading was useful as effectively reduced cooling need. Because of high investment cost, external shading was not economic to use, however it decreased cooling capacities significantly that was not accounted in economic analyses.

Based on the results the most energy efficient façade solutions were by orientation the following:

- South – 5 panes without external shading, WWR=60%, external wall insulation 390 mm
- East – 5 panes with external shading, WWR=60%, external wall insulation 390 mm

- West – 5 panes with external shading, WWR=60%, external wall insulation 390 mm
- North – 5 panes without external shading, WWR=60%, external wall insulation 390 mm

In cost optimal performance level, based on 20 years net present value calculation, the best energy performance was achieved with façade solutions:

- South – 3 panes without external shading, WWR=23.9%, external wall insulation 200 mm
- East – 3 panes without external shading, WWR=23.9%, external wall insulation 200 mm
- West – 3 panes without external shading, WWR=23.9%, external wall insulation 200 mm
- North – 3 panes without external shading, WWR=37.5%, external wall insulation 200 mm

For South, East and West facades the exact cost optimal point was achieved at WWR=37.5%, which increased primary energy and cooling load but due to lower window cost relative to insulated wall the NPV was slightly decreased. However, because of increased cooling load WWR=37.5% will need extra investments in room conditioning units or external shading which were not taken into account in cost optimal calculation. Therefore, for practical cost effective design, the conclusion is that WWR about 25% can be recommended for South, East and West facades, when the North façade needs about 40% WWR.

Quadruple windows with about 40% WWR and no external shading provided an interesting alternative in between cost optimal energy performance level with triple glazing and very expensive quintuple glazing. Increase in the net present value was not very high, and energy performance improvement from 4 to 5 panes was already quite marginal.

Limited number of simulations with Central European climate showed that similar solutions to Estonian cost optimal clearly outperform conventional design with double glazing, although cooling energy dominated instead of heating energy and also external shading was an effective means of reducing primary energy. Triple glazing with slightly larger size (WWR=37.5%) resulted in best energy performance and very large windows showed worse results compared to more reasonable sizes. In the case of less effective lighting system, the effect of large windows could be less negative.

6. Acknowledgement

The research was supported by the Estonian Research Council, with Institutional research funding grant IUT1−15, and with a grant of the European Union, the European Social Fund, Mobilitas grant No MTT74.

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Figure 1 The generic model of single floor of an office building constructed with 2.4 m room module – plan and 3D view. The locations of workplaces used for control of lighting are marked in the plan.

Figure 2 Floor plan of the open plan office module (2.4 m) and the section showing window and room height.

Figure 3 Section of external wall, the thickness on insulation varies by cases

Figure 4 Minimum window to wall ratio depending on visible transmittance of window glazing

Figure 5 Window sizes of glazing variants (Variant codes correspond to Table 2, e.g. 2/C 0.95 m 21.6% means double, highly transparent window with width of 0.95 m and the window-to-wall ratio 21.6%). 2.4 m is the maximum width of the window providing WWR 60%.

Figure 6 Energy need in zones with highly transparent and solar protection windows with minimum size according to the daylight criterion of 2%.

Figure 7 Delivered energy for the cases of Figure 5.

Figure 8 Primary energy for the cases of Figure 5 and 6.

Figure 9 Delivered energy results of the cases used to determine optimal WWR with initial fixed insulation thickness (200 and 300 mm for 3 and 4 pane respectively). Delivered energy is given in each zone as a function of window type, external shading, orientation and window size. Case codes are described in Table 2, e.g. 3/C/-/23.9% means 3-pane, clear solar protection glass, no external shading and WWR=23.9%.

Figure 10 Primary energy for the cases of Figure 9.

Figure 11 Investment cost and primary energy of different glazing (all without external shading) and external wall insulation cases. Insulation thicknesses from left to right 150, 200, 250, 300 and 390 mm if not otherwise specified.

Figure 12 Net present value and primary energy for the cases of Figure 11.

Figure 13 Energy needs of final simulation cases for all zones. Insulation thicknesses determined in Ch. 3.4 are used.

Figure 14 Delivered energy of final simulation cases.

Figure 15 Primary energy of final simulation cases.

Figure 16 Investment and primary energy of final simulation cases. Three upper curves are with external shading (marked with *e*) and lower curves with more cases without.

Figure 17 Net present value and primary energy of final simulation cases without external shading.

Figure 18 Office room cooling capacities of final simulation cases

Figure 19 Energy use fluctuation of the most energy efficient cases

Figure 20 Energy use fluctuation of the financially most feasible cases

Figure 21 Delivered energy in Paris. In two first cases the cost effective and most energy efficient façade solutions in Estonian climate are used. In other cases U-values were 1.1 for double glazing, 0.6 for triple glazing and 0.2 for external walls.

Figure 22 Primary energy in Paris for the cases of Figure 21.

Table 1 Input data of office rooms and HVAC systems for energy calculations.

Occupants, W/m^2	5
Equipment, W/m^2	12
Lighting, W/m^2	5
Temperature set point for heating and cooling	+21 and+25 °C
Air flow rate	1.5 $l/(s \cdot m^2)$; 35 l/s
Illumination setpoint at locations (x,y,z)=(2.2, 4.0, 0.9), lx	500
Total irradiance on facade above which solar shading is down, W/m^2	200
Frame ratio of windows, %	15
Heating system (radiators) efficiency, -	0.97
Heat source (district heating) efficiency, -	1.0
Cooling system losses, % of cooling energy need	10
Mechanical cooling SEER, -	3.0
Ventilation SFP, $kW/(m^3/s)$	1.3
Temperature ratio of heat recovery, %	80

Table 2 Description of clear and solar protection glazing variants and initial U-value of opaque elements of external walls.

	Glazing						
Variant	No of panes, coatings	U-value, $W/(m^2 \cdot K)$	g-value, -	Visible trans-mittance τ_{vis}, -	External shading	Initial U-value of external walls, $W/(m^2 \cdot K)$	Gas filling
2/C/-	2 low E	1.1	0.61	0.78	No	0.16	Argon
2/D/-	2 tinted solar	1.0	0.27	0.50	No	0.16	Argon
3/C/-	3	0.54	0.49	0.70	No	0.16	Argon
3/C/e	2xlow E	0.54	0.49	0.70	Yes	0.16	Argon
3/SC/-	3 Clear solar + low E	0.54	0.36	0.60	No	0.16	Argon
3/D/-	3 tinted solar + low E	0.54	0.24	0.45	No	0.16	Argon
4/C/-	4	0.32	0.36	0.63	No	0.11	Krypton
4/C/e	solar + 2xlow E	0.32	0.36	0.63	Yes	0.11	Krypton
5/C/-	5	0.21	0.24	0.56	No	0.11	Krypton
5/C/e	solar + 3xlowE	0.21	0.24	0.56	Yes	0.11	Krypton

Table 3 Cost data of opaque elements of external wall, which were concrete Sandwich elements with mineral wool insulation

Insulation thickness, mm	U-value, W/(m²·K)	Investment cost, €/m²
150	0.20	131.2
200	0.16	179.5
250	0.13	227.9
300	0.11	276.3
390	0.09	363.4

Table 4 Cost data of windows, including both glazing units and aluminum profiles with thermal breaks. The window sizes vary for different glazings which affects the development of window cost due to different proportions of frames. Window cost has been more thoroughly described in the companion paper [14].

Variant	Dimen-sions, mm	Gas between panes	U-value, W/(m²·K)	Solar factor g, -	Visible transmittance τ_{vis}, -	Investment cost, €/m²
2/Air	950 x 1800	Air	1.4	0.61	0.78	237.0
2/Arg		90% argon	1.1	0.61	0.78	244.3
3/Air	1050 x 1800	Air	1.1	0.52	0.71	240.0
3/Arg		90% argon	0.54	0.49	0.70	241.9
4/Kry	1150 x 1800	90% krypton	0.32	0.36	0.63	311.6
5/Kry	1300 x 1800	90% krypton	0.21	0.24	0.56	381.3*

*- The cost of quintuple glazing is hypothetical, the cost increase from 3 to 5 panes was taken into account as linear

Table 5 Investment cost of external wall as a function of insulation thickness and glazing type. All costs in the Table are investment costs per m² of conditioned floor area, €/m².

	Glazing type and WWR, %					
Insulation thickness, mm	2/Air 21.6%	2/Arg 21.6%	3/Air 23.9%	3/Arg 23.9%	4/Kry 26.1%	5/Kry 29.5%
150	91.1	91.9	91.8	92.3	100.8	-
200	94.3	95.0	94.8	95.3	103.8	-
250	-	98.1	97.9	98.4	106.8	-
300	-	-	-	101.5	109.8	121.7
390	-	106.9	107.2	107.6	116.2	127.9

Table 6 Final simulation cases

Variant	Glazing				Exterior wall U-value, W/(m^2·K)	WWR, %	External shading	Window width, m
	No of panes	U-value, W/(m^2·K)	Solar factor g, -	Visible transmittance τ_{vis}, -				
3/C/Ar/-	3	0.54	0.49	0.70	0.16	23.9/ 37.5	No	1.05
4/C/Kry/-	4	0.32	0.36	0.63	0.13	26.1/ 37.5* 60.0(N)	No	1.15/ 1.65**
5/C/Kry/-	5	0.21	0.24	0.56	0.09	29.5/ 37.5(W)/ 60.0**	No	1.30/ 1.65*
3/C/Ar/e	3	0.54	0.49	0.70	0.16	23.9*/ 37.5*	Yes	1.05
4/C/Kry/e	4	0.32	0.36	0.63	0.13	26.1*/ 37.5*	Yes	1.15
5/C/Kry/e	5	0.21	0.24	0.56	0.09	29.5*/ 37.5*** 60.0(W)	Yes	1.30/ 1.65*

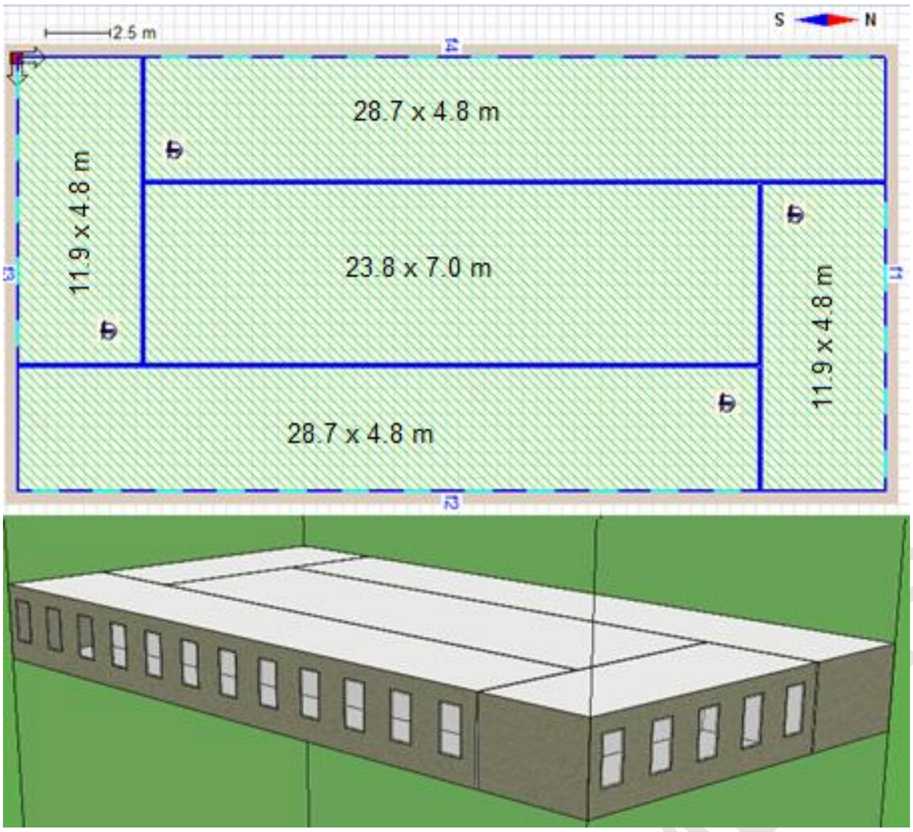
*- South, east and west façades only

** - South, east and north facades only

*** - South and east facades only

(N) - North façade only

(W) - West façade only



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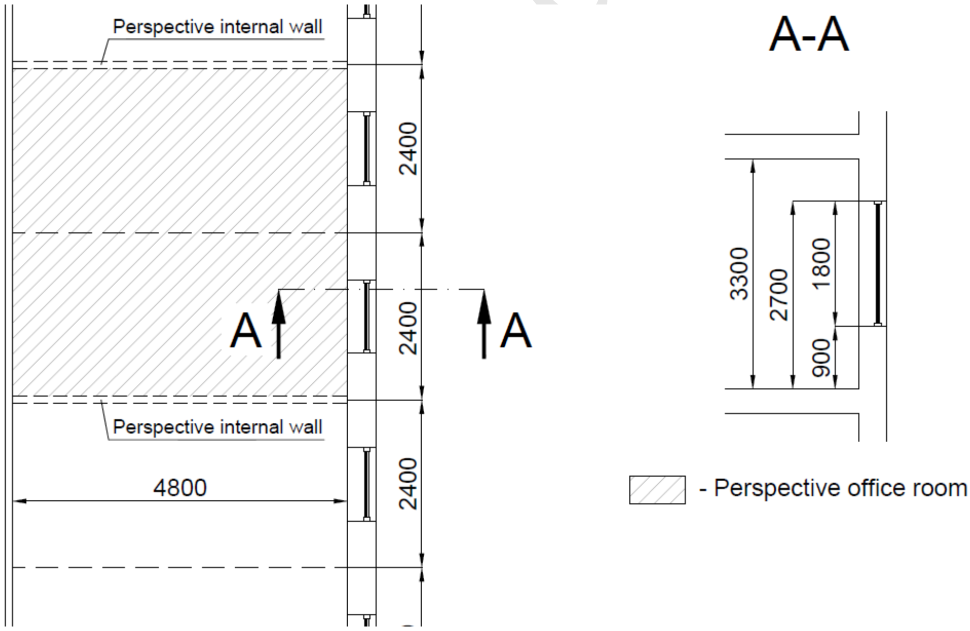


Figure 2 Floor plan of the open plan office module (2.4 m) and the section showing window and room height.

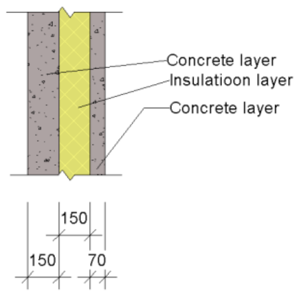


Figure 3 Section of external wall, the thickness on insulation varies by cases

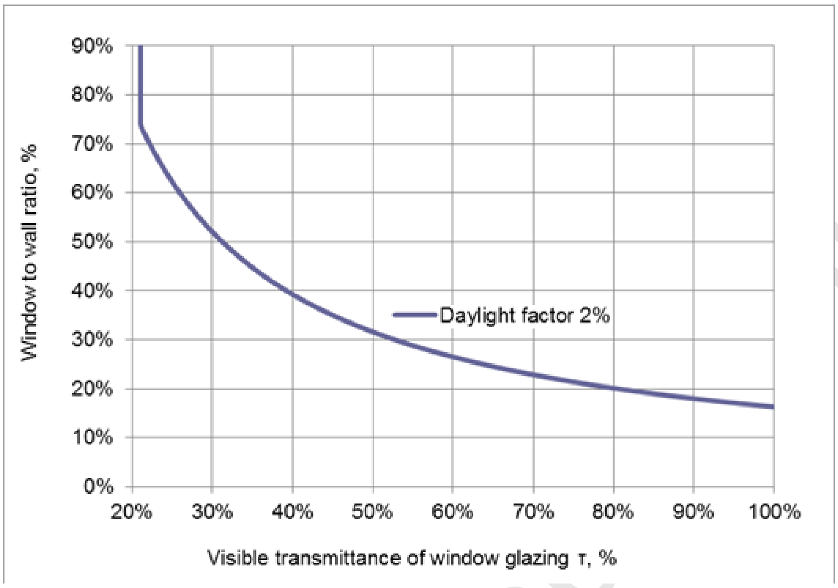
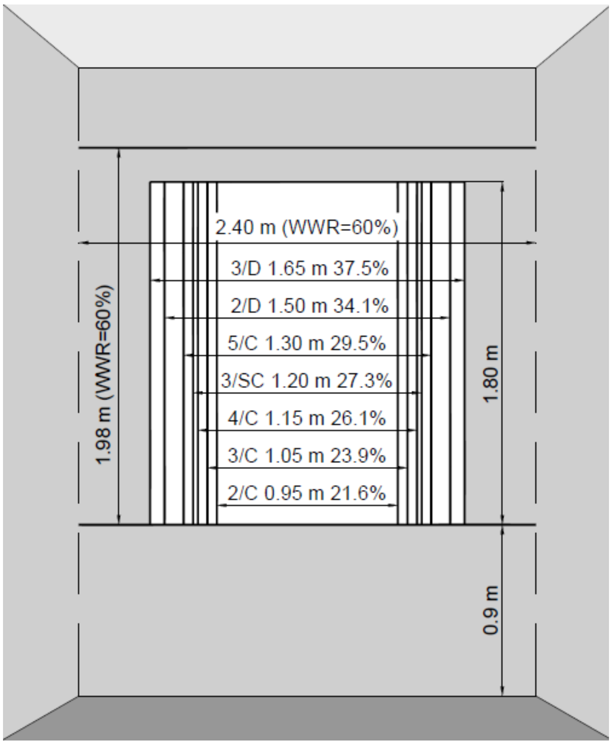


Figure 4 Minimum window to wall ratio depending on visible transmittance of window glazing



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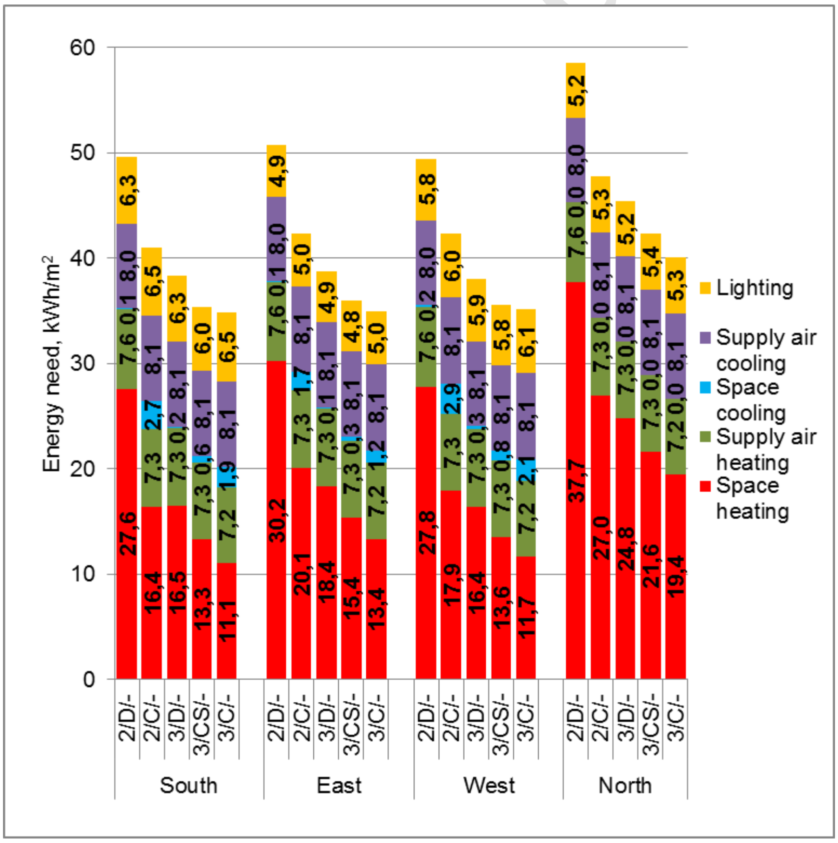


Figure 6 Energy need in zones with highly transparent and solar protection windows with minimum size according to the daylight criterion of 2%.

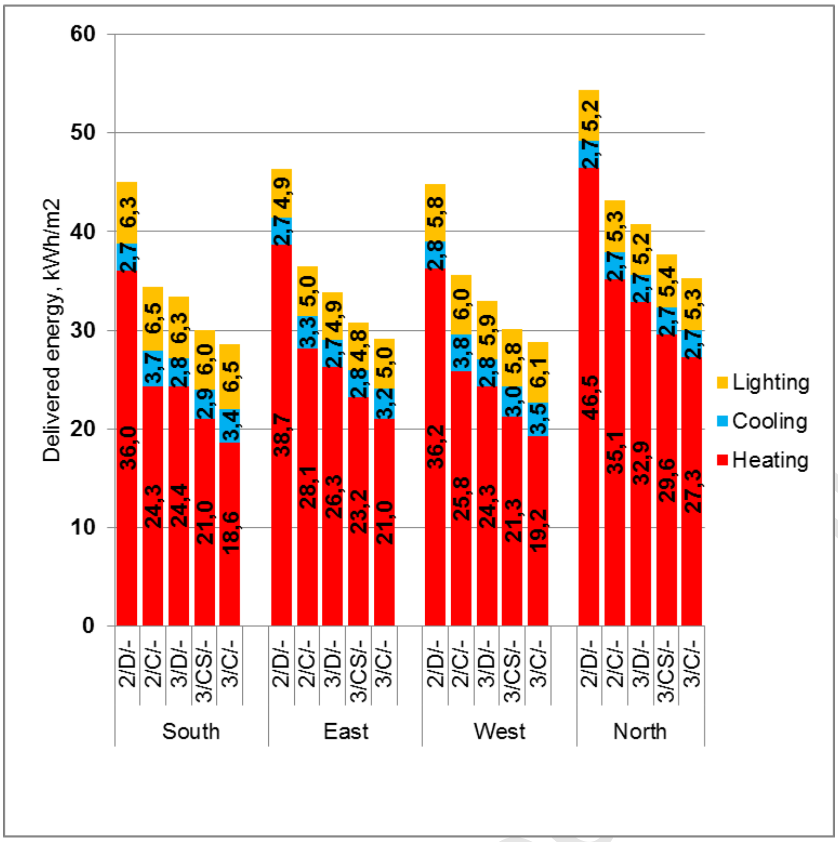


Figure 7 Delivered energy for the cases of Figure 5.

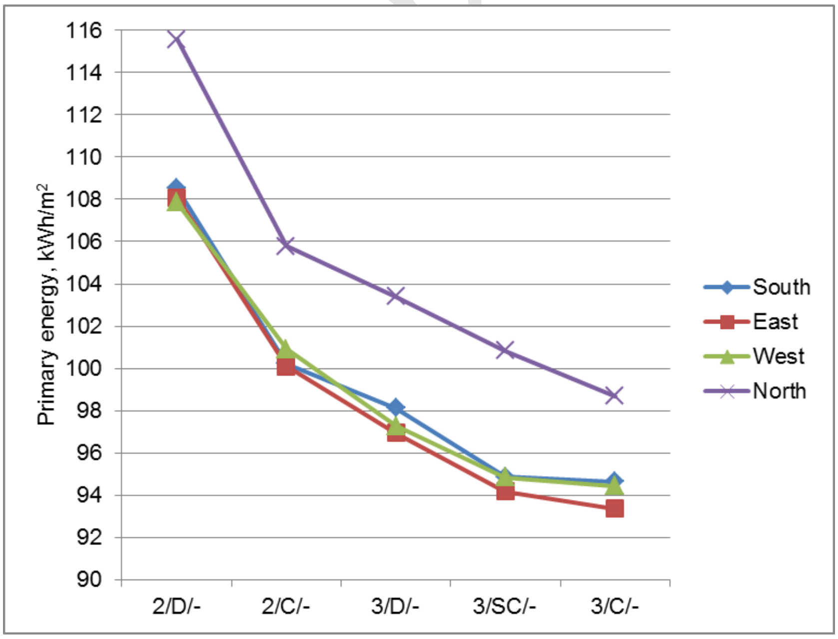


Figure 8 Primary energy for the cases of Figure 5 and 6.

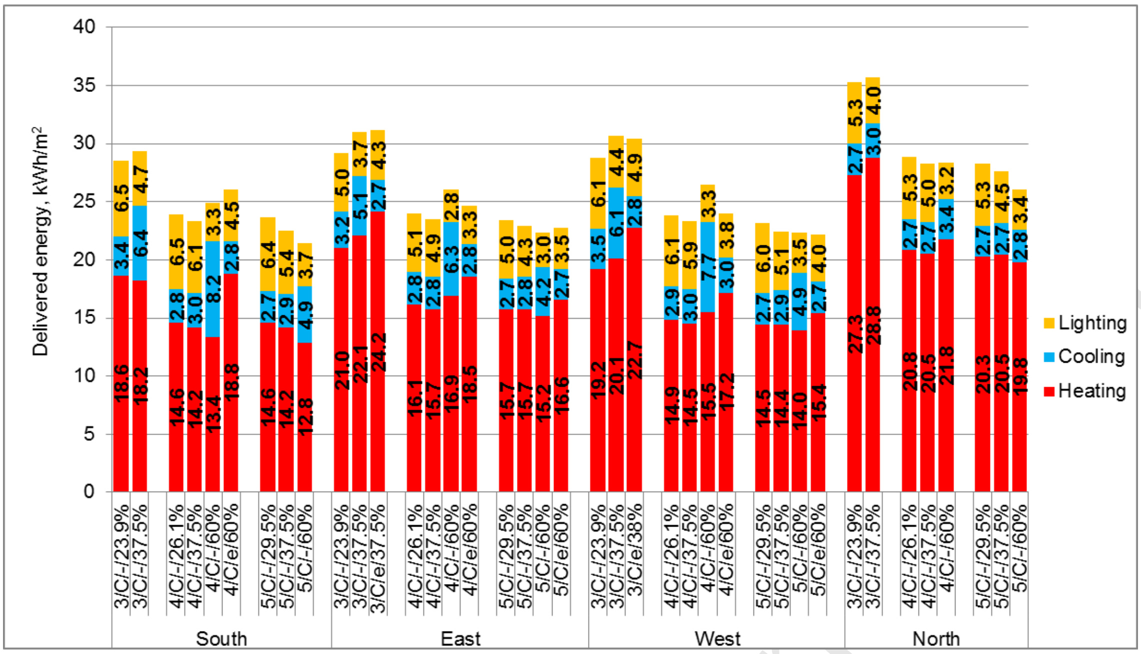


Figure 9 Delivered energy results of the cases used to determine optimal WWR with initial fixed insulation thickness (200 and 300 mm for 3 and 4 pane respectively). Delivered energy is given in each zone as a function of window type, external shading, orientation and window size. Case codes are described in Table 2, e.g. 3/C/-/23.9% means 3-pane, clear solar protection glass, no external shading and WWR=23.9%.

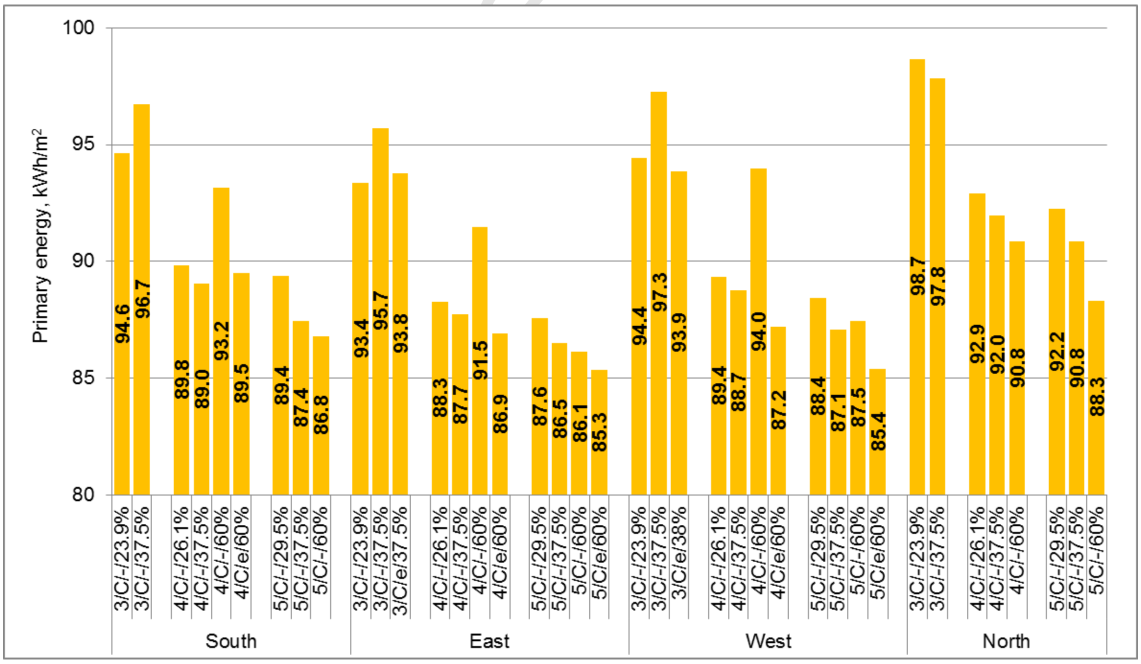


Figure 10 Primary energy for the cases of Figure 9.

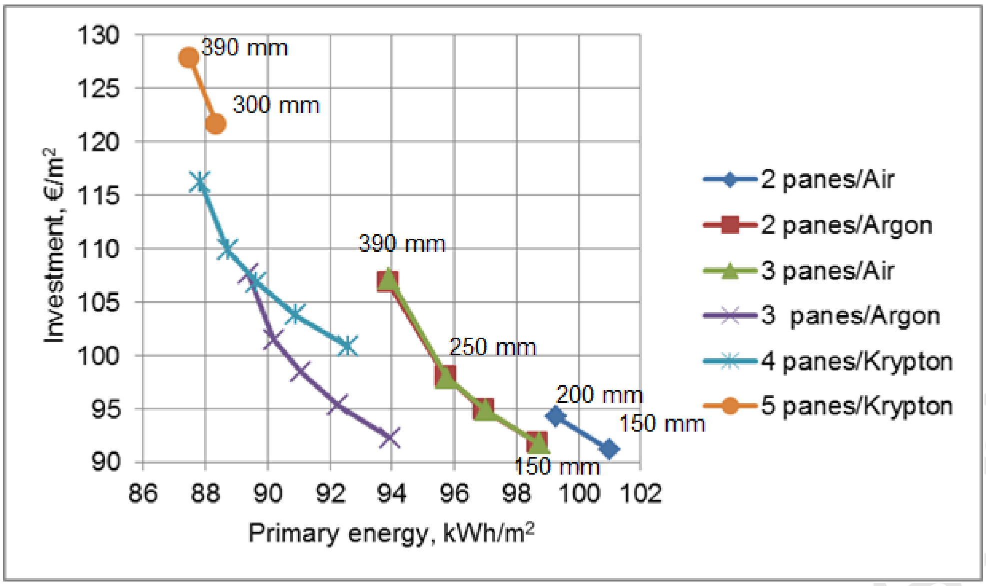


Figure 11 Investment cost and primary energy of different glazing (all without external shading) and external wall insulation cases. Insulation thicknesses from left to right 150, 200, 250, 300 and 390 mm if not otherwise specified.

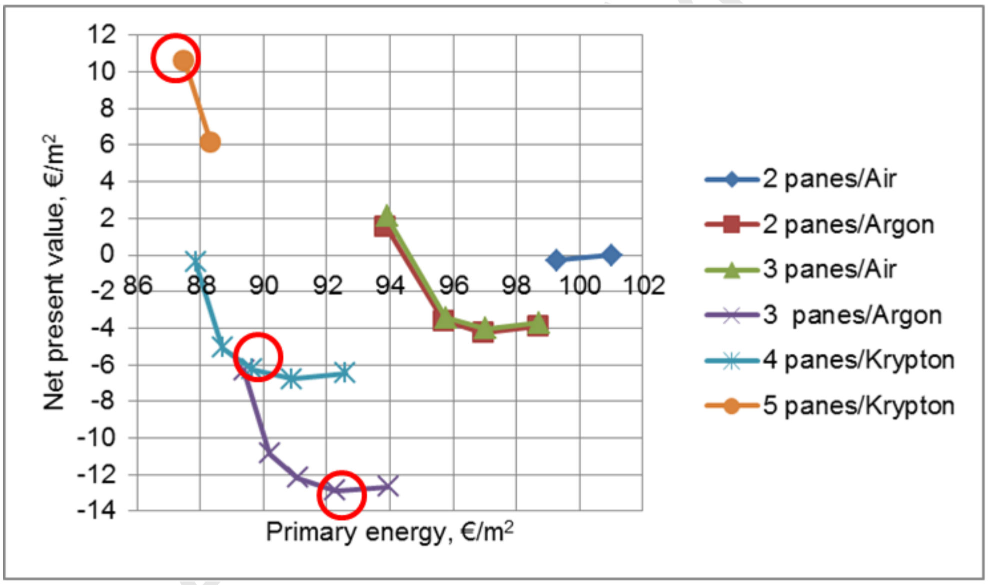


Figure 12 Net present value and primary energy for the cases of Figure 11.

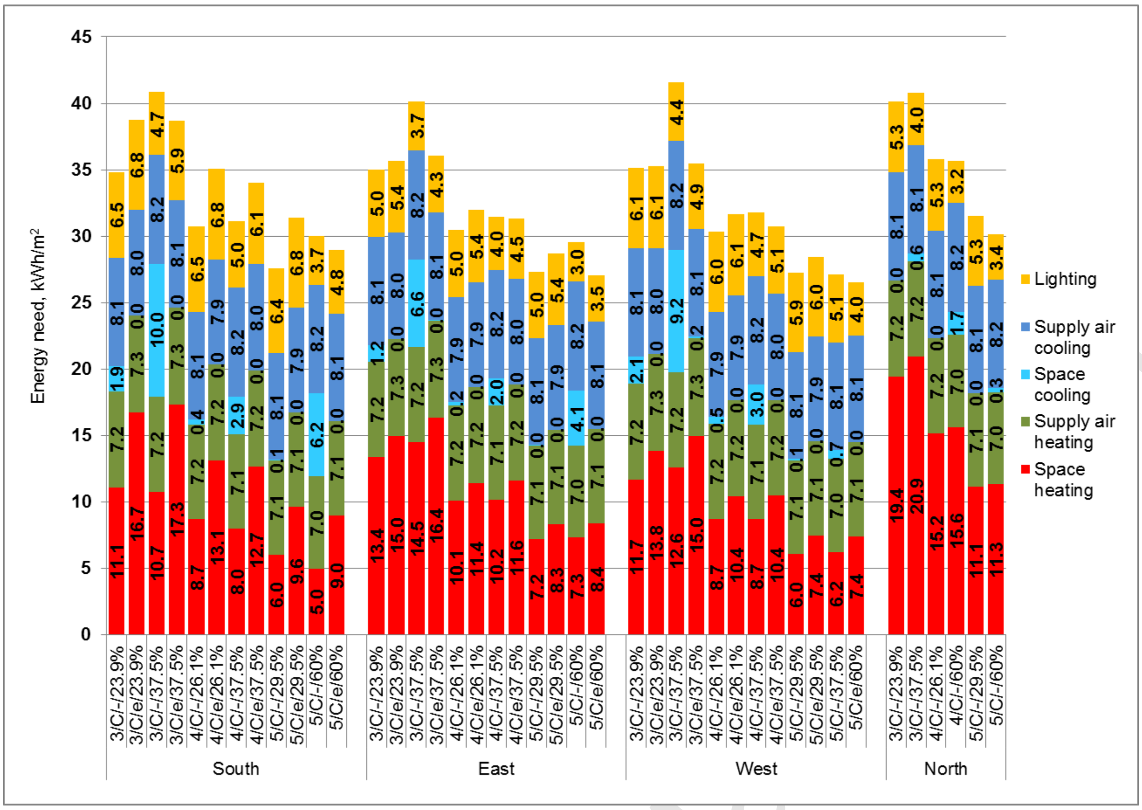


Figure 13 Energy needs of final simulation cases for all zones. Insulation thicknesses determined in Ch. 3.4 are used.

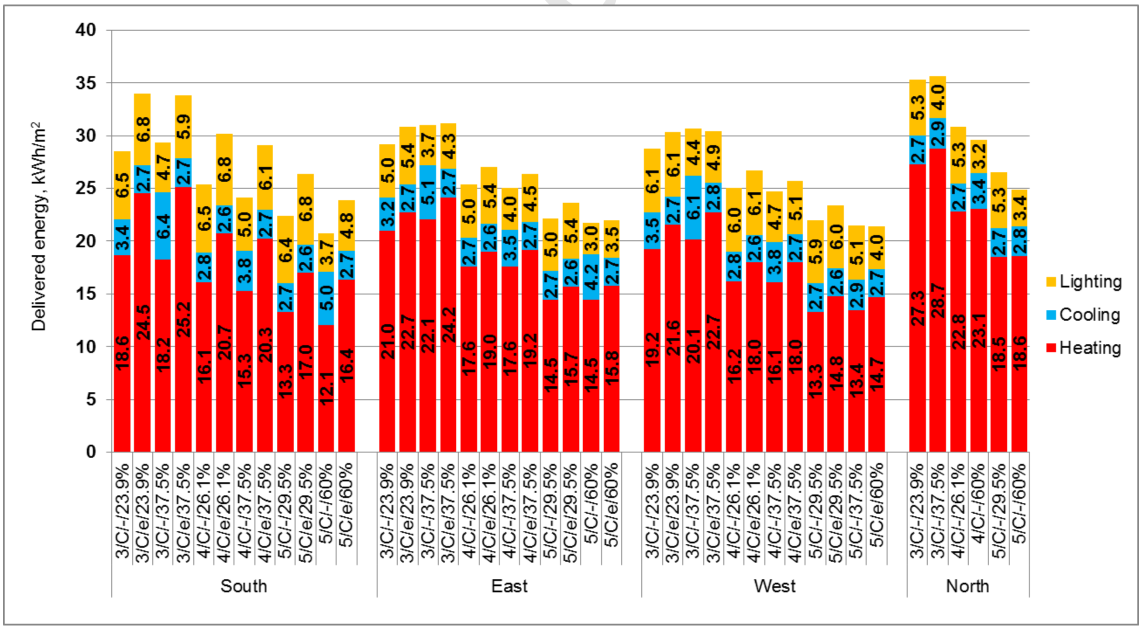


Figure 14 Delivered energy of final simulation cases.

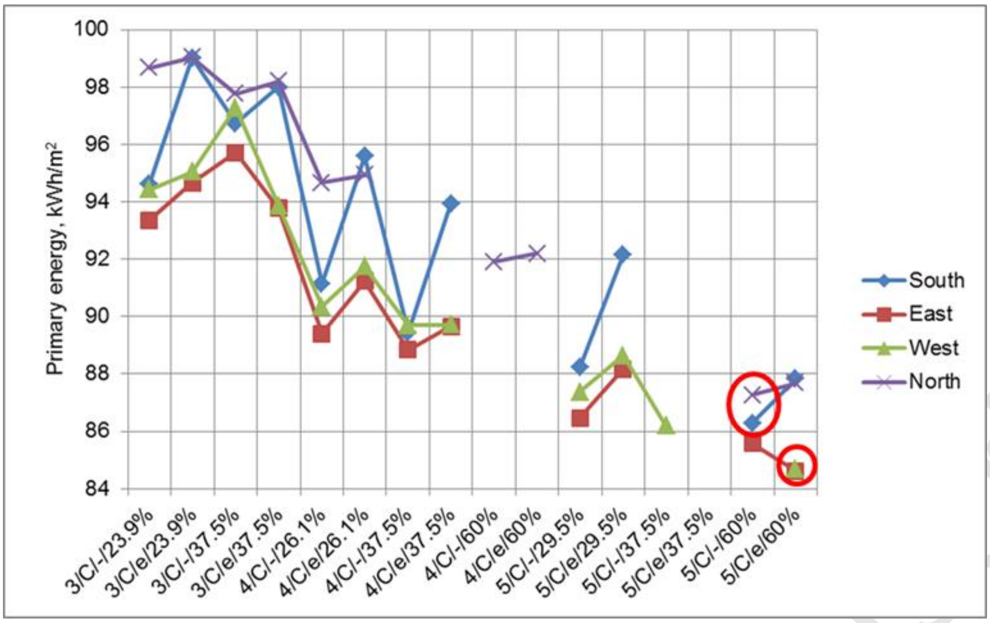


Figure 15 Primary energy of final simulation cases.

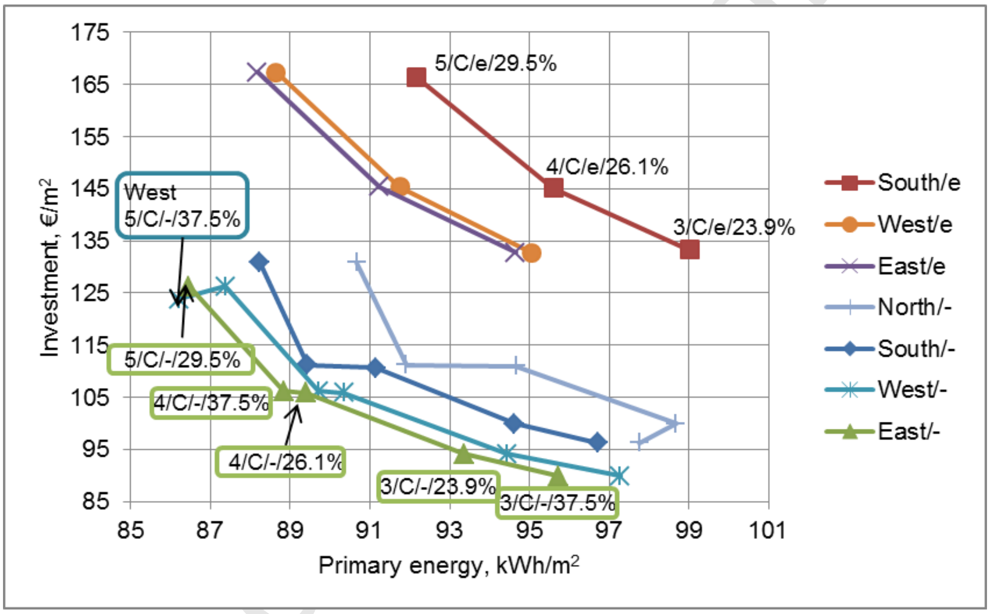


Figure 16 Investment and primary energy of final simulation cases. Three upper curves are with external shading (marked with *e*) and lower curves with more cases without.

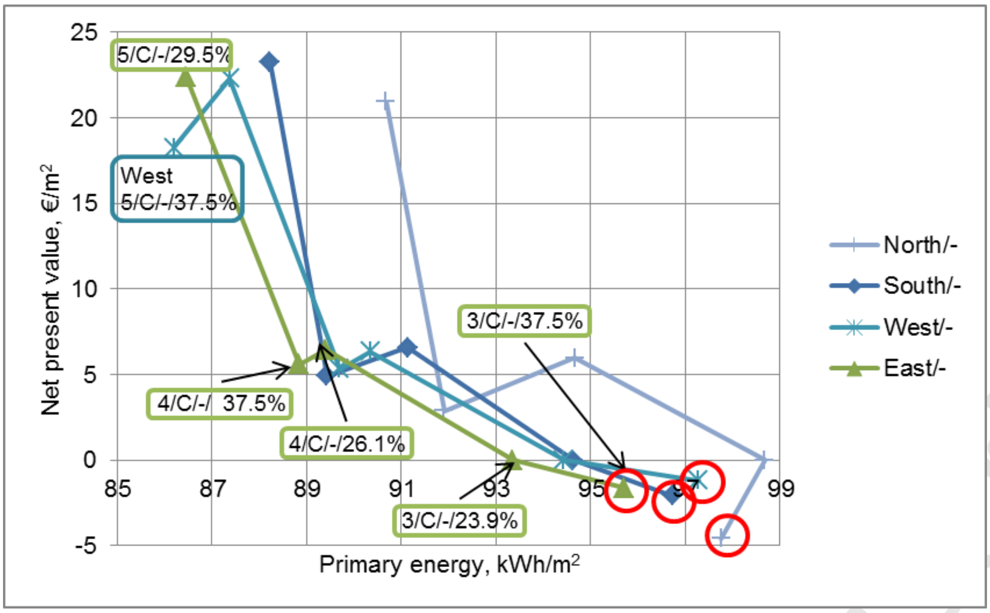


Figure 17 Net present value and primary energy of final simulation cases without external shading.

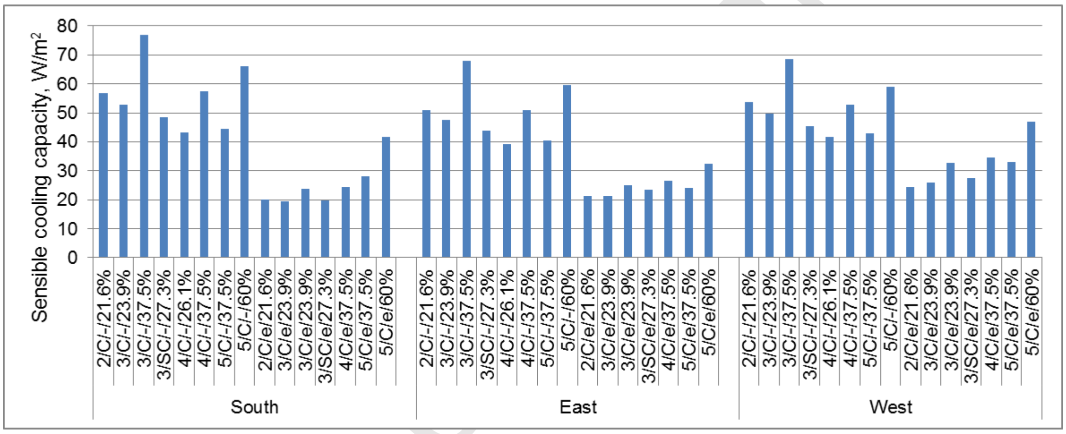


Figure 18 Office room cooling capacities of final simulation cases

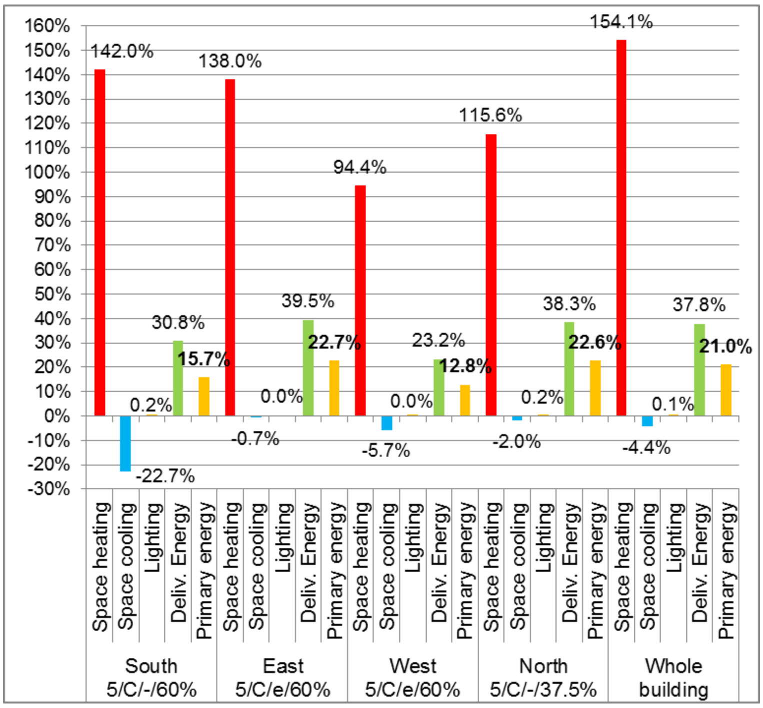


Figure 19 Energy use fluctuation of the most energy efficient cases

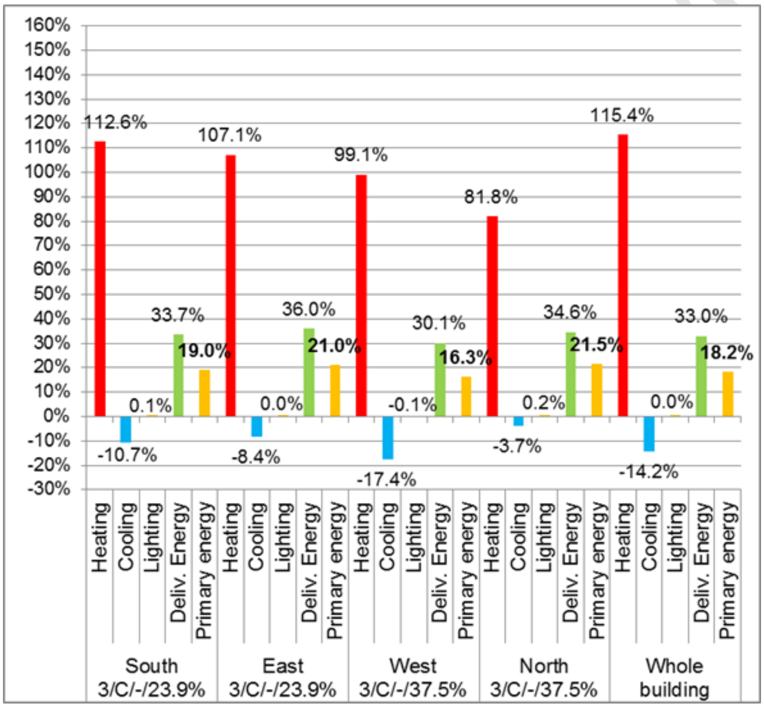
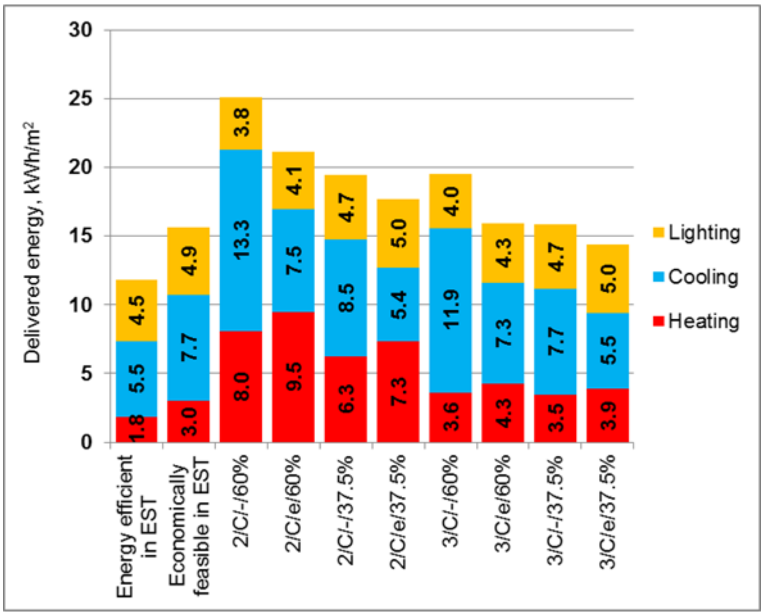


Figure 20 Energy use fluctuation of the financially most feasible cases



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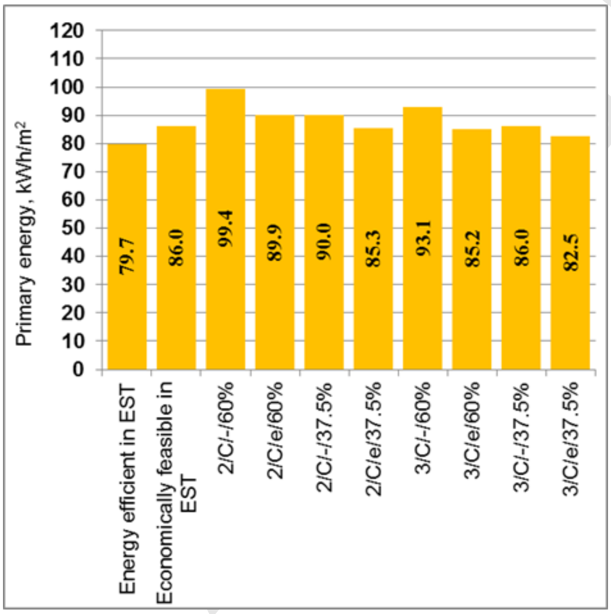

Figure 22 Primary energy in Paris for the cases of Figure 21.